Aalto University
School of Chemical Technology

School of Chemical Technology
European Mineral Engineering Course

Omar Velázquez Martínez

# DYNAMIC SIMULATION OF A MODULAR FLOTATION PLANT

**Master’s thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 10 August, 2016.**

**Supervisor** Professor Rodrigo Serna

**Instructor** M. Sc. Jussi Leinonen

**Aalto University**
**School of Chemical Technology**

**Aalto University, P.O. BOX 11000, 00076 AALTO**
**www.aalto.fi**

**Abstract of master's thesis**

**Author** Omar Velázquez Martínez

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**Thesis supervisor** Professor Rodrigo Serna

**Thesis advisor(s) / Thesis examiner(s)** M. Sc. Jussi Leinonen

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**Abstract**

The aim if this thesis work is to develop a dynamic simulator tool of a modular flotation plant with the final purpose of the simulator to be used as a training tool for operators. The thesis report describes basic theory about froth flotation process, process modelling, automated control and the development process of the final simulator tool. The simulator tool was developed for Outotec Oy® Finland based on their designs and calculations.

The simulator was developed with the aid of three different programs: HSC Sim 9, SIEMENS PCS 7, Virtual Experience Manager and Virtual Experience Client. HSC Sim performs dynamic simulation of the flotation process. SIEMENS PCS is the Distributed Control System (D.C.S.) where the automated control, the human machine interface and the instrumentation are created. The final training platform development and training exercise creation was done using Virtual Experience Manager. Virtual Experience Client was used to activate the training simulator tool.

The final version of the training simulator was capable of simulating the required flotation flowsheet with the input ore-feed. It can be used as a base platform on which further development regarding instrumentation, flotation circuit and mineral processing can be modified to fit different configurations as required. Further development of the simulator requires improvement on the capabilities of the programs used for the development.

**Keywords** Froth Flotation, Dynamic Simulation, Automated Process Control, Training Simulator, Operator Training.

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KIITOS.

GRACIAS.

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# 1. Introduction

Froth flotation is the presently most important mineral recovery and upgrading process. Flotation provides recovery of valuable minerals from low grade, highly complex ores and refractory ores, permitting the mineral processing industry to obtain economic growth from that kind of ores. (Wills and Napier-Munn 2006, Bulatovic 2007, Remes, Advanced Process Monitoring and Control Methods in Mineral Processing Application 2012, Drzymala 2007).

Process automated control, modelling and simulation have increased their importance in the mineral processing industry in the last 40 years with the introduction of automated control in beneficiation, comminution, flotation plants, etc. (Wills and Napier-Munn 2006). Their importance increased with their application in flotation plant simulation, control in flotation process as well as environmental and operational hazards and safety among others (Lamberg, et al. 2009, Moilanen and Remes 2008, Deng and You 2011). Process automated control improves the stability of processes. Process modelling and simulation increase the knowledge aiming to predict process and overall behaviour without the need of running tests.

The present economic conditions, low metal prices, the need of improvement on the recovery of valuable minerals from low-grade ores, government environmental regulations and corporative goal of expense reduction are pushing the mineral processing industry to use automated process control and automation into their processes (Bulatovic 2007, Wills and Napier-Munn 2006, Seborg, et al. 2011). The automated process control is capable of increasing the recovery of metal from the ore.

The application of process control, automation, modelling and virtual simulation in the mineral processing has been studied since 1980's. Ever since there have been developments which, worked out by industry, academia applied into mining operations with positive results. They cover areas of safety education and training, simulation of flotation circuits as well as control of flotation circuits (Deng and You 2011, Kaartinen, et al. 2013, Moilanen and Remes 2008, Lamberg, et al. 2009, Roine, Kaartinen and Perti 2011).

The benefits from applying process automated control include economic gain from reduction of training time operators in both new and operating plants. For sites under development, an efficient virtual simulation of the process enables its overall understanding of it, potentially offering a glance of the possible problems during the start-up phase, shutdowns, unusual process disturbances, and may provide guidelines regarding the most efficient ways to operate the plant (Seborg, et al. 2011).

This thesis intends to apply process control, automation, modelling and virtual simulation of an actual froth flotation plant with the objective to create a functional virtual operator-training platform tool. The virtual training tool will be based on the Outotec OY® modular flotation circuit design flowsheet, piping and instrumentation diagram (PI-diagram) and mechanical design. At the end the operator-training tool is expected to simulate the modular flotation plant behaviour in real time, to be capable of development training exercises and permit interaction between user and plant instrumentation and installed machinery.

The dynamic modelling, flotation cell dimensioning, and flotation dynamic simulation models of the flowsheet are present in Outotec's® own simulation platform called "HSC Sim 9®". The development of process control logic was realized by using the Siemens'® distributed control system, DCS, software "PCS 7®". Finally, the development of the virtual operator-training tool was based on Outotec's "Virtual Experience Manager®" and "Virtual Experience Client®". For the purpose of this thesis "HSC Sim9®", "SIEMENS PCS®", "Virtual Experience Manager®" and "Virtual Experience Client®" programs were classified as platform, and the training program developed was defined as a simulator.

This thesis is divided into 3 main sections. The first section is chapter 2 titled: Background: Simulation of Froth Flotation describes basics of froth flotation as a separation method and process control, modelling and dynamic simulation. This section introduces basic flotation principles, hydrophobicity flotation reagents, flotation cell technology, followed by process control, process automation and dynamic simulation principles and dynamic simulation applied to froth flotation.

The second section, chapter 3 titled: Development of Dynamic Training Simulator for a Modular Flotation Plant describes the development process of the virtual training simulator. This process involves three stages: from i) creation of the flotation circuit simulation flowsheet in static and dynamic modes using "HSC Sim 9®", ii) development of the process control logic and Human Machine Interphase (HMI) in "PCS 7®", and iii) creation of the virtual training tool in "Virtual Experience Manager®" and "Virtual Experience Client®" environment. This section includes the description of a realized case study where the training simulator was introduced to Master's degree students from Aalto University and the platform was modified based on the feedback received.

Finally the third section, chapter 4: Results and Conclusions, summarizes the final outcome of the developed training operator tool, its capabilities and limitations. Describes possible further development of the training platform.

## 2. Background: Simulation of Froth Flotation

Minerals processing is a branch of science which deals with the extraction, handling and upgrading of mineral ores with the purpose of obtaining a high purity final concentrate (Wills and Napier-Munn 2006). To obtain an economically viable final concentrate the extracted ore has to go through several processes, liberation, sizing and upgrading. Liberation and sizing processes are focused in reducing of the particle size to liberate the valuable minerals from the gangue minerals. The upgrade stage is focused on the separation of mineral species and the recovery of different valuable mineral species.

The upgrading (beneficiation) methods separates the mineral species by interacting their chemical and/or physical properties of the minerals with the fields provided by a separator. Typical separation processes are gravity concentration, dense media separation, magnetic and electrical separation and froth flotation. These methods utilized different properties of the minerals. For example, i: difference in specific gravity of each mineral, ii: difference in specific gravity relative to a heavy media, iii: difference in diamagnetic and paramagnetic properties and presence of ferromagnetic minerals, iv: hydrophobicity and hydrophilicity of minerals (Wills and Napier-Munn 2006).

Froth flotation is a complex process which is not yet fully understood (Drzymala 2007) with complicated interactions among the ore feed minerals, water phase, added reagents and dissolved ions (Wills and Napier-Munn 2006). Under these circumstances conducting experiments to understand the effect of a single change on the recovery consumes man power and finances.

In an effort to diminish the overall investment, time, economic resources and man power, the industry has developed computer platforms which can simulate a mineral processing plant (King 2001). For instance, platforms such as *Modsim Plant Simulator* (Technologies 2010)*, Outotec HSC* (Outotec, Outotec 2016)*, JKSimfloat* (JKTech 2011). Such platforms have helped the industry to understand their own processes (Kaartinen, et al. 2013).

This thesis project is focused on the simulation of a froth flotation concentration plant. Therefore, this chapter will describe both knowledge on flotation as well as process simulation and control. Next, a concentration plant will be simulated using HSC Sim9® and the simulation controlled using Siemens PCS7®.

## 2.1. Froth Flotation

Froth flotation is the most important upgrading method in the minerals processing industry for the recovery of valuable minerals from complex ores. Since its creation, over a 100 years ago (Bulatovic 2007), froth flotation allowed to turn low grade and complex ores, previously thought as uneconomic, into economically feasible for extraction and upgrade (Wills and Napier-Munn 2006).

Flotation is a combination of physical, chemical and physiochemical phenomena in a three-phase that is mineral particle/liquid/gas phase system, as presented schematically in Figure 1 (Bulatovic 2007). The success of the flotation separation is closely related to the specific chemical and physical characteristics of each of the phases.

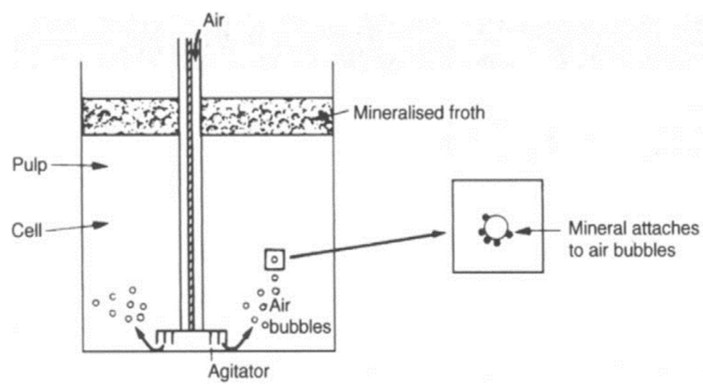


*Figure 1 Attachment of a mineral particle & phases in flotation cell (Wills and Napier-Munn 2006).*

Separation by froth flotation can be conducted by three different mechanisms i) true flotation, ii) Entrainment, and iii) Entrapment. Improving the efficiency of froth flotation involves a fourth mechanism known as drainage (Wills and Napier-Munn 2006).

True flotation is the most important mechanism of froth flotation and it represents the majority of valuable mineral particles recovered, nonetheless, entrainment and entrapment mechanisms collaborate in recovery of minerals.

True flotation is the attachment of the particle to the air bubble by the effect of the hydrophobicity of the mineral particle. The attachment of the mineral particles to the bubble takes place in the pulp zone of the flotation cell, as shown in figure 1. The mineral particle-bubble interphase is transported to the froth phase of the cell, as shown in figure 1. The mineralized froth is then separated by the flotation cell launder. The mechanical aspects of the flotation cell will be covered in section 2.2.

Entrainment and entrapment mechanisms take place in the froth zone. The entrainment of mineral particles, either values or gangue, occurs in the water phase while going through the froth. The entrapment of mineral particles is a result of valuable mineral particles attachment to gas bubbles (Wills and Napier-Munn 2006). The drainage effect occurs for un-attached particles suspended in the froth zone to return them to the pulp zone. Drainage is intended to have a greater effect on gangue minerals than valuable minerals (Wills and Napier-Munn 2006).

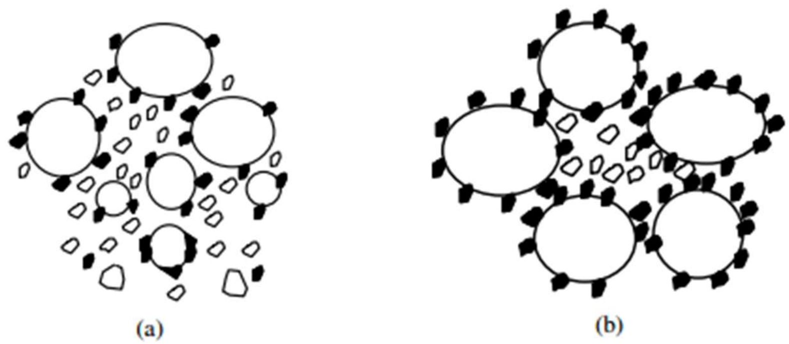


*Figure 2 a) entrainment mechanism. B) entrapment mechanism (Konopacka and Drzymala 2010).*

The true flotation mechanism is the selective attachment of the mineral particle to the gas bubble, as displayed in Figure 1. This mechanism depends on chemical and physical interactions between the different existent phases: mineral particle, liquid and gas and surface properties of the different mineral species (Wills and Napier-Munn 2006).

The attachment of the valuable mineral to the bubble depends on a mineral surface property called hydrophobicity. Hydrophobicity is described by Drzymala (2007) as the ability to repel, to some extent, water. According to Bulatovic (2007), hydrophobization is a process of selectively converting the surfaces of particular minerals from a hydrophilic condition to a hydrophobic condition. The physical property that directly influences the attachment of the mineral particle to the air bubble is contact angle, as shown in Figure 3 (Wills and Napier-Munn 2006).

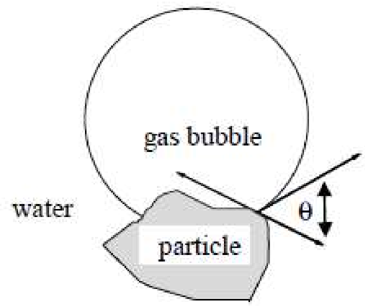


*Figure 3 Attachment of a mineral particle to a gas bubble (Drzymala 2007).*

Hydrophobicity is measured by two different interfacial phenomena: surface electrochemistry and wettability. Surface electrochemistry in the form of zeta potential and wettability as contact angle (Bulatovic 2007).

### 2.1.1. Contact Angle

Contact angle is defined by as the angle formed in an aqueous environment by the air-bubble attached to the surface of the solid, shown in figure 6 (Wills and Napier-Munn 2006). The tensile forces in the system, while in equilibrium state, lead to the formation of the angle θ in the water-air phase, equation (1). The angle is the quantitative measurement of the hydrophobicity of a material and an indirect reference to its floatability.

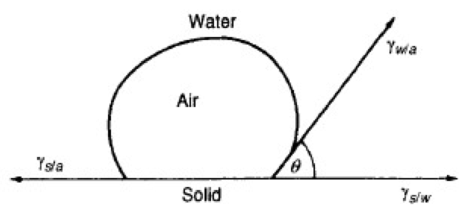


*Figure 4 Contact angle between bubble and particle in liquid media (Wills y Napier-Munn 2006).*

$$\gamma_{s/a} = \gamma_{s/w} + \gamma_{w/a} \cos\theta \qquad (1)$$

where $\gamma_{s/a}$, $\gamma_{s/w}$and $\gamma_{w/a}$ are the surface energies between solid and gas phases, solid and liquid phases and liquid and gas phases respectively and $\theta$ is the contact angle formed between the mineral surface and the gas bubble due the hydrophobicity of the mineral surface (Wills and Napier-Munn 2006).

While the system is under equilibrium state, it can be represented by equation (1). The system, however, can break the equilibrium state and separate into two different two-phase systems: solid-water and air-water. Evidently, in the case of flotation the mineral will not float and there will be no separation of ore from gangue under these circumstances since there is no solid-gas interaction. The force required to keep the particle attached to the bubble is called "work of adhesion" and is calculated using equation (2) (Wills and Napier-Munn 2006).

$$W_{s/a} = \gamma_{w/a} + \gamma_{s/w} - \gamma_{s/a} \qquad (2)$$

where $W_{s/a}$ is the work of adhesion $\gamma_{s/a}$, $\gamma_{s/w}$ and $\gamma_{w/a}$ are the surface energies between solid and gas phases, solid and liquid phases and liquid and gas phases respectively. Equations (1) and (2) can be combined to form:

$$W_{s/a} = \gamma_{w/a}(1 - \cos\theta) \qquad (3)$$

From equation 3, it is observable that the greater contact angle, θ, the stronger the attachment between mineral particle and gas.

Unfortunately, most of valuable minerals are not naturally hydrophobic and flotation reagents have to be added to the flotation process to enhance their hydrophobicity and floatability. The term hydrophobicity refers to the mineral's surface property while the term floatability refers to the kinetic characteristics of flotation of the mineral particles (Leja 1982, Laskowski 1986, Woods 1994).

Different reagents are used during froth flotation to promote the attachment of minerals to the gas bubble, hence improving the separation process. The most important reagents are collectors, frothers and regulators and are described in general terms below (Bulatovic 2007):

i. Collectors: they affect the flotation process by selectively adsorb onto the desired minerals. The formed collector layer will render the mineral surface hydrophobic, increasing the probability of attachment of the particle to the air bubble, hence flotation will increase and improve the separation (Bulatovic 2007). Depending on the ability to dissociate into water collectors can be divided in two groups:
   - *a.* Ionizing. This type of collector can dissociate into water.
   - *b.* Non-ionizing. This type of collector does not dissociate into water.

ii. Frothers: Frothers are compounds that aim at rendering bubbles that are stable enough to transport minerals into the froth phase, mainly by lowering the surface tension of water. Frothers also affect directly the size of the gas bubbles. The use of frothers also result in a more stable froth phase increasing the probability of drainage of gangue minerals (Bulatovic 2007, Wills and Napier-Munn 2006).

iii. Regulators: Their main action in froth flotation is to modify the action of the collector on the mineral surfaces, inducing either hydrophobicity or hydrophilicity of the solids. Depending on whether they promote or prevent the adsorption of collectors, regulators are referred to as activators or depressants. Consequently, by action of regulators, the separation process will be more selective process (Bulatovic 2007).

### 2.1.2. Zeta Potential

Zeta potential or electro kinetic potential value is used to determine the action of adsorbed collectors onto the minerals' surface (Bulatovic 2007). Zeta potential is measured from the surface electrochemistry effect known as electrical double layer (EDL). The E.D.L. is the formation of two ionic zones on the surface of the mineral particle, as displayed in Figure 5.

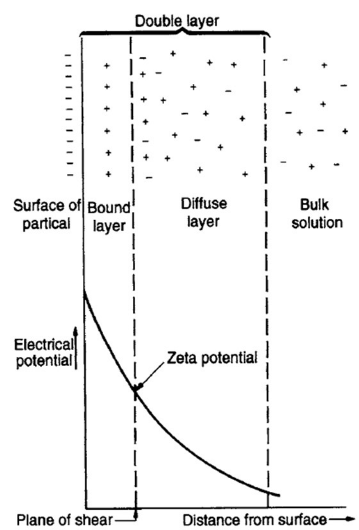


*Figure 5 Electrical Double Layer and Zeta Potential (Wills and Napier-Munn 2006).*

The environment ions are attracted to the mineral's surface because of the effect of the minerals' surface charge, displayed negative in figure 5, forming the bound layer, displayed as positive in figure 5. The diffuse layer is formed as a consequence of the bound layer.

At rest, the system's bound layer and diffuse layers compensate each other to achieve electrical neutrality. When the system is agitated the bound layer remains with the particle while the diffuse layer is altered, hence the electrical neutrality is removed (Wills and Napier-Munn 2006). The difference in electric charges between the bound layer and the environment creates what is known as zeta potential (Bulatovic 2007). The zeta potential value of a mineral particle can change depending on the pH (free electrolytes) of the environment, as displayed in figure 6.

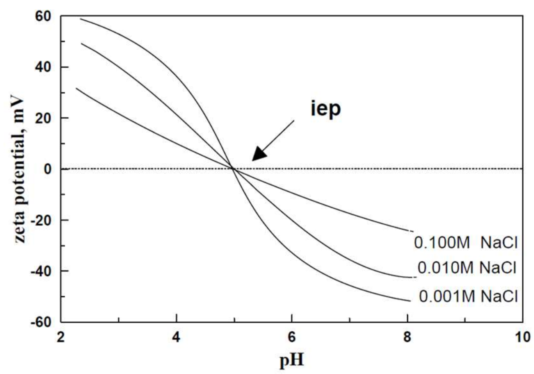


*Figure 6 Zeta Potential as a function of pH and concentration of electrolyte in the solution. The isoelectric point (iep) is also shown (Drzymala 2007).*

As can be inferred from figure 6, depending on the pH of the environment the electrical charge and zeta potential of the mineral surface can change. Hence depending on the pH of the environment the collector can be adsorbed to the mineral and render hydrophobic the mineral's surface. The flotation process can be controlled to separate the different minerals in the same process by controlling the pH of flotation line phases.

The pointed "iep" point in figure 6 stands for Isoelectric point. This is a vital point for the mineral, it is the value of pH where the surface changes from having a positive charge to a negative charge or vice versa. By knowing the iep pH value it can be defined the type of collector that can be used in for the specific mineral's flotation.

### 2.1.3. Liberation and Flotation kinetics

Several factors affect the efficiency of the froth flotation process, including the liberation of the valuable mineral particle is a very important factor for the flotation process (Wills and Napier-Munn 2006, Bulatovic 2007). The liberation of the valuable mineral is the extraction, by comminution of the valuable mineral, from the host rock, as the figure 7 shows.

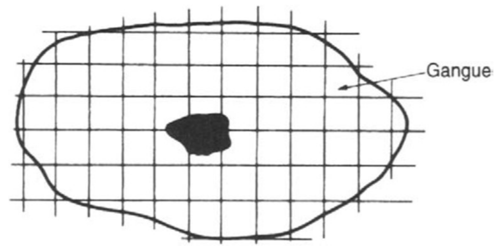


*Figure 7 Valuable mineral "locked" in gangue host rock (Wills and Napier-Munn 2006)*

The comminution process is not entirely perfect and a single ore fragment can produce non-uniform product particles as can be seen in figure 8 (Wills and Napier-Munn 2006). Each of the products has their own flotation properties.

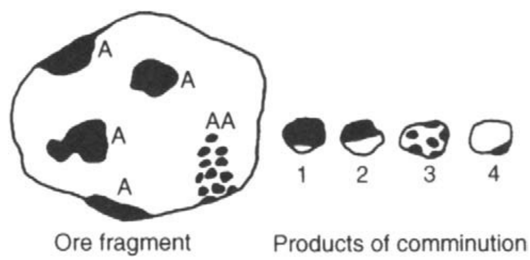


*Figure 8 Products of comminution (Wills and Napier-Munn 2006)*

Since the attachment of the valuable mineral particle to the bubble surface is directly affected by the valuable mineral surface available, it can be inferred that the more liberated a valuable mineral is, the less time it takes to float (Wills and Napier-Munn 2006). The characterization of the rate of flotation in a cell is called flotation kinetics. The flotation kinetics are unique in every separation process and this, kinetic models require values that are typically measured experimentally. Flotation kinetics are affected by the use of chemical reagents (Wills and Napier-Munn 2006).

Different mathematical models have been created regarding flotation kinetics. For the purpose of the training platform development. In this work a three-component model was used for the flotation cells. The details of the model will be described in section 3.1.1.

## 2.2. Flotation Cell Technology

Industrially, flotation takes place in tank cells, with volumes ranging from <3 $m^3$ to 630 $m^3$ with continuous feed of slurry circulating (Outotec, Outotec 2016). A flotation cell is a stirred tank with inputs of slurry (feed) and gas (air feed) and with outputs of concentrate and tailings. Its main mechanical assembly consist of a tank, a stator/rotor, a shaft, input and output valves, a motor and a drive, as exemplified in Figure 9.

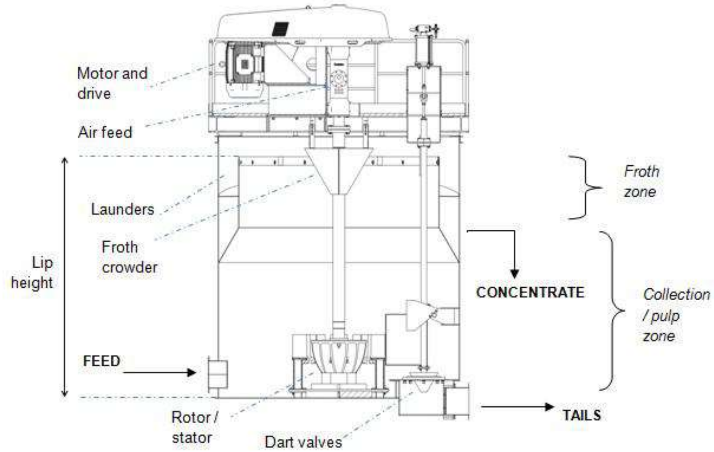


*Figure 9 Flotation cell with main components (Remes, Sim Minerals Processing Unit Models 2016).*

The operation of the flotation tank cell is divided in two zones: the pulp zone and the froth zone. In the pulp zone the slurry and air is fed and agitated by the rotor. The bubbles are created by the air delivered to the bottom of the tank. The agitation of the slurry and the formed bubbles increases the probability of attachment of the mineral particle to the gas bubble. In principle, the froth zone contains the valuable minerals attached to the bubbles, yet gangue particles can be carried on to the froth zone by effect of entrainment and entrapment as mentioned in section 2.1. The depth of the froth zone also increases the possibility of drainage of entrapped gangue. After the bubbles reach the top of the froth zone, they are dropped to the launders and to the concentrate stream.

Generally, a single industrial scale flotation cell tank does not perform an efficient separation. The first stages of a flotation circuit generally carry in the froth phase unwanted gangue minerals carried by different means, entrapment and multiphase ore. The multiple phase ore minerals occur during the process of comminution which is never perfect. The comminuted mineral particle is, in reality, never formed only by valuable mineral but different minerals attached (Bulatovic 2007). Hence it is needed to connect two or more flotation cells (Wills and Napier-Munn 2006). A series of connected flotation cells called a bank. Its operation is displayed in figure 10.

In the bank displayed in figure 10 the slurry is fed to the first flotation cell and processed, the first concentrate is dropped in the launder and the tailings are sent to the next flotation cell. During this process a flotation cell must accomplish, according to Ek (1992), five functions: i) formation of a homogeneous pulp, ii) introduction of air and formation of bubbles, iii) agitation of the pulp to induce contact between mineral particles and bubbles, iv) transfer the mass from cell to cell and finally v) formation of stable forth (Wills and Napier-Munn 2006).

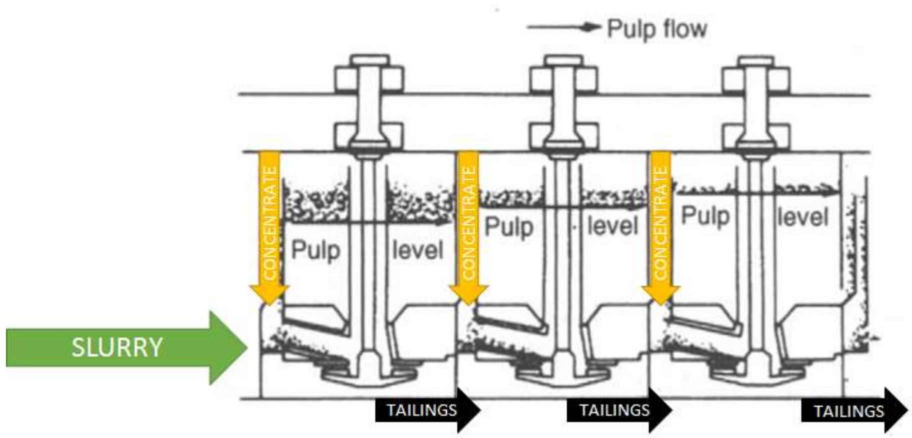


*Figure 10 Bank of flotation 3 cells connected in series based on Wills and Napier-Munn (2006)*

## 2.3. Process Automation Control, Modelling and Dynamic Simulation

Industrial processes have been, since their creation, under a constant evolution. This regards also the mineral processing industry. Since the patent of flotation technology in 1906 it became the most important concentration technique (Remes, Advanced Process Monitoring and Control Methods in Mineral Processing Application 2012). Along with the evolution of industrial processes their increased complexity. As a process grows in complexity, its stability will likely be negatively affected as a larger number of variables require to be controlled. As the control of large or complex systems becomes more challenging, the industry has reached for more efficient methods than those offered by traditional manual control.

Present industry requirements caused by the global competition and changing economy for a faster production development, stricter environmental and safety regulations, lower production and man labour costs, high operational training costs and ramp up costs and the need for increased recovery from low grade ores, have pushed the mineral processing industry into applying process control in beneficiation plants and simulation based training for their staff (Seborg, et al. 2011, Remes, Advanced Process Monitoring and Control Methods in Mineral Processing Application 2012, Ogunnaike 1994). Without process control and process automation any present manufacturing, mining, mineral processing process would not be possible to control and to run efficiently (Seborg, et al. 2011). Process control and process automation aid directly to the stabilization of the process by leaving fast decision making to automation tools, reducing non-operative times, implementing changes in production lines faster and reducing the amount of staff required to operate a plant.

This chapter intends to describe the principles of process control and dynamic simulation and their application in a flotation circuit with the purpose to fully understand the project development section (section three). For the purposes of this thesis, the definition of a process is that of Seaborg et al. (2011): "*The conversion of feed material to products using chemical and physical operations. In practice, the term process tends to be used for both, the processing operation and the processing equipment".* The feed material is the extracted ore, water and reagents, chemical and physical operations are the flotation process itself and the processing equipment is a flotation cell, as it is described in the previous section.

### 2.3.1. Process Automation

Process automation is the use of automation tools to control the parameters and stabilize the results of a process. In the early days of plant control was entirely human based (Seborg, et al. 2011, Ogunnaike 1994). However, present development of plant design requires them to be larger, more complex and with larger equipment (Oravainen 2000). The need of control increased with the process complexity, nowadays it is impossible to control, for example, a beneficiation plant or a froth flotation process with man-based control because of the large number of process variables, complexity of the process, valves to control, input and output streams (Seborg, et al. 2011). A process under automated control can produce higher quality, operate with higher consistency, competitiveness and with less breakdowns (Sharma 2011).

Technologies, as Programmable Logic Controllers, PLC, and Distributed Control Systems, DCS, represent a major aid on the control of excessively complex processes by automation. These two tools, as control models, can either work separately or in combination (Siemens Energy & Automation 2007).

Both tools can control a process or a plant automatically. Nevertheless, depending on the dimensions and complexity of the process DCS or PLC can be more suitable for it. Table 1 shows a comparison of some features of PLC and DCS.

*Table 1 Differences between PLC and DCS features, based on Siemens Energy & Automation (2007).*

| **Programmable Logic Controller, PLC.** | **Distributed Control System, DCS.** |
|---|---|
| • Batch process orientation.<br>• Typically used in assembly.<br>• Operators can see the process.<br>• Fast response.<br>• Suitable for single unit applications.<br>• Operator role is to handle exceptions.<br>• The *Controller* is the heart of the operation.<br>• Suitable for simple PID<br>• Alarm system display when the process in interrupted. | • Continuous process orientation.<br>• Typically used in transformation of raw materials<br>• Operators cannot see the process.<br>• Slow response.<br>• Suitable for plant wide applications.<br>• Operator role is to make decisions.<br>• The *HMI* is the heart of the operation.<br>• Suitable from simple to complex PID up to Advanced Process Control<br>• Alarm system tailored to send warnings. |

In spite of the evident differences in both systems they can be applied together, known as a hybrid control system. This type of system leaves the hardware control (actuators) to the PLC part while the DCS works as a regulatory control (Siemens Energy & Automation 2007).

Hybrid control systems have direct application to mineral processing industry. There are different platforms to generate the automated control of a process; for the purpose of the experimental part, Section 3, the used platform is SIEMENS PCS 7®, more details about it will be discussed in the mentioned section.

### 2.3.2. Process Control

The aim of process control is to maintain any process under stable conditions during a constant period of time. Stabilizing an actual process is not an easy task. To control a full process, it is required to understand and characterize it. Characterization of a process is performing the identification of three following process variables (Seborg, et al. 2011, Ogunnaike 1994):

a. Controlled Variables (CV): Process variables that we can control, are also referred to as set-point. For instance, in a flotation cell it will be throughput, ore feed tonnage, reagent dosing, tank level, among others.
b. Manipulated Variables (MV): Process variables that are modified in order to keep the process in the set point and/or drive the controlled variable to it. For instance, increase or decrease of tonnage, flow rates of air and water etc.
c. Disturbance Variables (DV): Process variables that affect the controlled variables and cannot be manipulated or removed, also called noise. They are inherent to any process. For instance, specific mineral composition of the ore in the moment of addition, room temperature etc.

Controlled variables and manipulated variables are information that can be defined and measured from the process, unlike disturbance variables or noise, which by definition can be measured but cannot be controlled. When the variables are defined, a proper control system must 1) acquire information from the plant, 2) process the information, 3) take a decision upon the difference between measured variables and their corresponding set point and 4) perform the proper adjustments in site acquired to the decision taken (Ogunnaike 1994). Figure 11 shows a general schematic representation of the flow of information in any manufacturing process and the explained components of a control system.

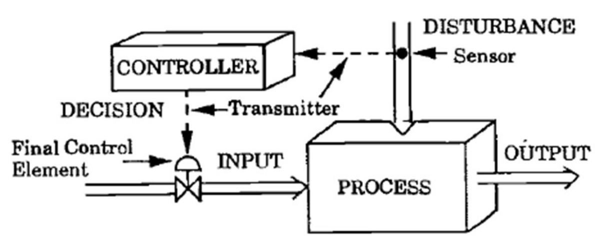


*Figure 11 Feedforward control system (Ogunnaike 1994)*

The status of the process is read by sensors. Sensors are physical instruments that acquire all the information by physical measurement of a specific property and send it in form of electric signals to the controller. They can measure temperature, pressure difference, flow, composition, level difference, etc.

The communication between the process and the controller is performed by transmitters. Transmitters capture the information from the field, sent to the controller, the controller makes the decision and sends the corresponding change to the process' instruments. In this group, we can include signal converters. These elements modify the measured signal for instance, from electrical signal into a pneumatic signal. In addition, they are able to change electrical signals from analogue signal into digital or digital into analogue.

The decision makers or controllers are the core of a control system. They are the elements capable of making the decision on how to change the parameters according the received information. The decision making process can be carried in several different choices depending on the control structure and the control algorithm; such will be expanded in the next section.

Final adjustments in the process are hold by the final control elements. These are the actuators, valves, pumps, compressors, etc. Their task is to modify the controllable process variables so that the measured values approach the set point. Figure 11 shows the flow of information in any manufacturing process and the explained components of a control system.

#### *2.3.2.1. Process control strategies*

Depending on the desired flow of information and the specific process stability requirements, different control strategies can be implemented. For industrial applications the most important strategies are called feedback and feedforward (Ogunnaike 1994, Seborg, et al. 2011).

In the feedback control the change in the input is done based on the result, no corrective action is done until the alteration of the process happen. Corrective action to variations is taken regardless of the nature of the variations, whether the variation comes from a measured process variable or not. Figure 12 represents a tank with a feedback control strategy. The measured variable, tank output flow, is measured with an instrument, marked AT in figure 12, electrically transmitted to the controller which controls the input valve. The final action is done by the control valve after controller's decision.

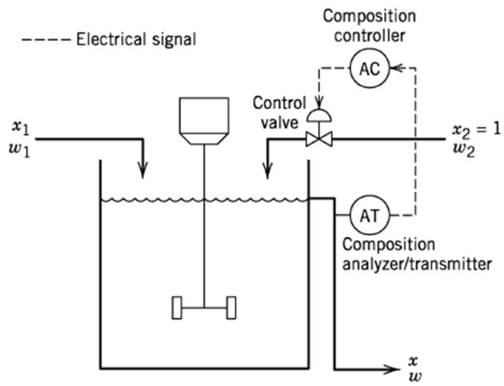


*Figure 12 Feedback control strategy applied on a tank (Seborg, et al. 2011).*

Feedforward control is the opposite of feedback strategy. In feedforward a variable, feed flow rate, is measured before it is introduced into the process. This approach stabilizes the balance among the input variables correcting variables and taking actions before a control action is done; hence the output is stabilized. Ideally, feedforward removes the disturbances before they happen, yet this strategy has three major disadvantages a) the disturbance has to be precisely measured, b) for unmeasured disturbances there is no correction action taken and c) a process model is required. Figure 13 represents a tank with a feedforward control strategy.

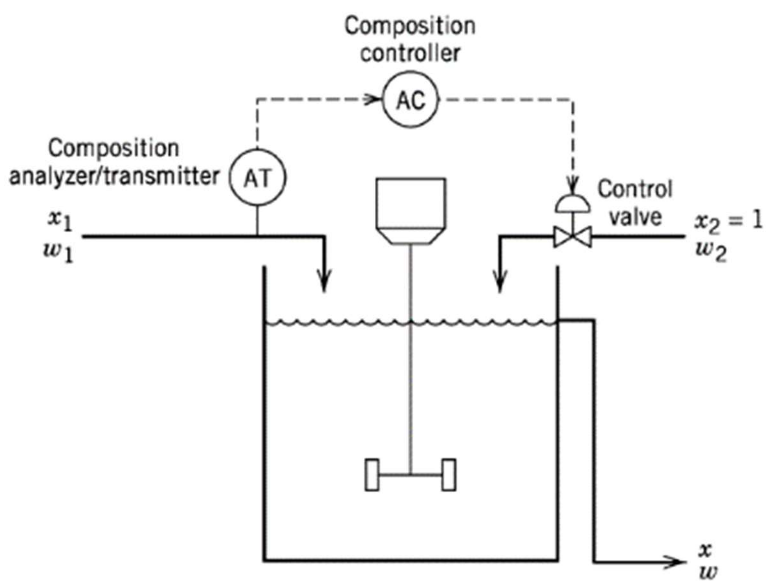


*Figure 13 Feedforward control strategy applied on a tank (Seborg, et al. 2011).*

Both strategies can be applied into the same process resulting in a more measured, stable process, although the control design will be more complicated.

### *2.3.2.2. Feedback control and control algorithms*

The feedback control strategy consists on measuring the controlled variable, the measured value is used to control the manipulated variable (Seborg, et al. 2011) with the objective of reducing the total error signal to zero, mathematically demonstrated in equation 4.

$$e(t) = y_{sp}(t) - y_m(t) \qquad (4)$$

where *e(t)* is the error signal, $y_{sp}(t)$ is the set point and $y_m(t)$ is the measured value of the controlled variable.

For the developed project, feedback strategy covers the control requirements for the equipment, flotation tank cell and pump sumps. In this project's case the tank levels and the pump sump levels are the controlled variables, they are measured and the manipulated variable are the output valve opening, as shown in figure 14. The more open the valve is, the faster the level will decrease, the more closed the slower.

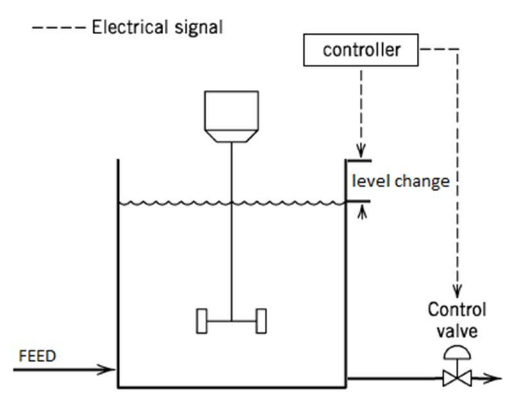


*Figure 14 Level control in a stirred tank based on Sebort et al. (2011)*

This strategy can perform the decision-making action based on four different algorithms. Those can be i) Proportional Control (PC), ii) Integral Control (IC), iii) Proportional Integra, iv) Derivative Control (DC) and v) Proportional Integral Derivative Control (PID). PID is being the most used in the industry (Seborg, et al. 2011) and it holds characteristics from the other type of control algorithms, PC, IC and DC. They all will be explained in this section. Figure 15 terminology will be used explain the control models.

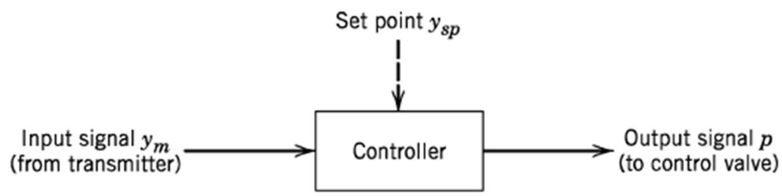


*Figure 15 Diagram of any feedback controller (Seborg, et al. 2011)*

Proportional Controller. A proportional controller means that the controller output is proportional to the error signal, equation 5.

$$p(t) = \bar{p} + K_c e(t) \tag{5}$$

Where *p(t)* is the controller output, $\bar{p}$ is the steady state value and $K_c$ is the controller gain. In this control mode the controller gain, Kc, can be adjusted to make the output more or less sensitive to the change, also the sign, ±, of the gain can be chosen to increase or decrease the output as the error signal increases (Seborg, et al. 2011). Ideally proportional control mode behaves linearly having the slope value of the gain, Kc. This control mode has the advantage of responding immediately as an error takes place; yet a disadvantage is inherent to this model, an *offset* or *steady-state error* in the controller occurs after there is a change in the set point or after a constant disturbance occur. The offset can take the control mode out of range or operation and useless for process control.

For integral control, the controller output depends on the integral of the error signal over time. Equation 5 for proportional control mode changes into equation 6, which expresses an integral component in the error value.

$$p(t) = \bar{p} + \frac{1}{\tau_I}\int_0^t e(t^*)dt^* \tag{6}$$

Where in equation 5, the user defines the value of $\tau_I$ which is called integral time or reset time. This value represents the frequency of integration. Integral control operates by changing the p value with time, hence bringing the error value to zero. The major benefit of Integral control is the removal of the *offset*. Nevertheless, integral control mode is an improvement compared to proportional, it contains the disadvantage of falling into a *saturation point.* A saturation point occurs when the disturbance or set point is larger than the range of the manipulated variable. Integral Control represents an improvement to Proportional Control but it does correct the error immediately as soon as an error is detected.

Integral control is rarely used by itself (Seborg, et al. 2011), but a combination of PC and IC is typically implemented. The combination is known as Proportional-Integral Control, equation 7.

$$p(t) = \bar{p} + K_c \left( e(t) + \frac{1}{\tau_I} \int_0^t e(t^*) dt^* \right) \qquad (7)$$

In Proportional-Integral control mode, the change in *p* is instant (time = 0), caused by the proportional component in equation 6. The integral effect in the control takes over when time increases. The integral part repeats itself every $\tau_I$ interval, hence the integral part has to be calibrated, and for instance, 5 cycles per minute is equivalent to $\tau_I$ value of 0.2. In spite of the benefits of proportional integral control, it contains a disadvantage. The model tolerates only a certain amount of oscillations, because it is associated with a fast response, which affects the integral part of the controller. This can be avoided by a proper tuning of the controller or integrating a *derivative control component* (Seborg, et al. 2011).

Derivative control mode aims to predict the future error in the process by considering its rate of change. This strategy equation is as following:

$$p(t) = \bar{p} + \tau_D \frac{de(t)}{dt} \qquad (8)$$

Similar to Integral controller and proportional integral controller, derivative controller contains a τD, which is a derivative time. Equation 7 changes the output p as a result of the rate of change of error in as a function of the time. The main advantage of this model is the predictability and adaptability to the future, the improvement in dynamic response and the reduced time to reach a steady state (Seborg, et al. 2011). Nevertheless, this model is highly sensitive to random fluctuations and high oscillations. A constant behaviour in either, random fluctuations or high oscillations, will cause the control to make erroneous decisions about the process; for this, the information sent to the controller has to be signal filtered before.

The final and the dominant control model is the Proportional Integral Derivative Control (PID), figure 16 represents the most common version of PID (Seborg, et al. 2011).

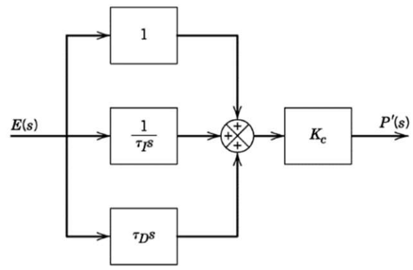


*Figure 16 Block diagram of a parallel form of PID (Seborg, et al. 2011).*

PID control model is the majorly used control for flow rate and liquid level applications, hence it is the selected model for the experimental section (Desborough and Miller 2002). As can be understand there are several ways to control a process depending on the requirements of it; Additionally, the model selection process itself can be in different approaches a traditional approach and a model based approach (Seborg, et al. 2011).

The traditional approach consists on the selection of the control system based on the knowledge of the process and the experience of the personnel. The control system is set up after the process is installed and running, maybe even stabilized. The major problem about this approach is that the process may not be under an optimum operation, even if stable.

The model based approach states the use of a dynamic model of the process to develop the control system design. A dynamic model can help in several ways, three of the major ones stated by Seborg, et al. (2011). i) It can be used as the basis model for model-based controller design method, ii) the dynamic model can be incorporated directly in the control law and iii) the model can be used in a computer simulation to evaluate the alternative control strategies and to determine the preliminary values of the controller settings.

### 2.3.3. Process Modelling and Dynamic Simulation

It is virtually impossible to discuss simulation without mentioning modelling. Process modelling is the process of creation a mathematical model, either static or dynamic, of any process. Process simulation is the application of those models in a virtual environment to estimate the behaviour of the process.

Any mathematical model has its limitations, and it is worth knowing it is limited by the amount of information that the modelling program capable to handle, yet the model cannot fetch all the variables of the real process either macroscopic or microscopic (Seborg, et al. 2011, Ogunnaike 1994). The main difference between a static or dynamic behaviour model is that the latter takes into consideration the effect of time on the system (Seborg, et al. 2011).

A model should only take into consideration the necessary process variables and assumptions. More variables and the model becomes excessively complicated while considering fewer than required and it makes it over simplistic (Seborg, et al. 2011). Either of these can lead into a non-valid approach for the problem and lead to an erroneous calculations and results.

Dynamic models can be of three types: i) theoretical models, ii) empirical models and iii) semi-empirical models (Seborg, et al. 2011).

i. Theoretical models: created based on theoretical knowledge of the process.
ii. Empirical models: created by fitting experimental data. These models can inaccurate results when extrapolating.
iii. Semi-empirical models: combination of theoretical models and empirical models. The numerical values of the parameters in a theoretical model are calculated from experimental data.

Regardless of the model type, a model creation is based on the *conservation laws*. The conservation laws cover i) *conservation of mass, ii) conservation of component I and iii) conservation of energy.* These three laws can describe any chemical process (Seborg, et al. 2011, Bulatovic 2007).

$$i. \{rate\ of\ mass\ accumulation\} = \{rate\ of\ mass\ in\} - \{rate\ of\ mass\ out\} \tag{9}$$

$$\text{ii. } \{rate\ of\ I\ accumulation\} = \{rate\ of\ I\ in\} - \{rate\ of\ I\ out\} + \{rate\ of\ I\ produced\} \tag{10}$$

$$\text{iii. } \{rate\ of\ energy\ accumulation\} = \{rate\ of\ energy\ in\ by\ convection\} - \{rate\ of\ energy\ out\ by\ convection\} + \{net\ rate\ of\ heat\ addition\ to\ the\ system\ from\ the\ surroundings\} + \{net\ rate\ of\ work\ performed\ on\ the\ systems\ by\ the\ surroundings\} \tag{11}$$

Solving the model of a process is not an easy task and the complexity of the model depends on the developing engineer (Ogunnaike 1994). Calculations, depending on the detail of the model, can take valuable time and economic resources (Remes, Advanced Process Monitoring and Control Methods in Mineral Processing Application 2012, Seborg, et al. 2011).

Computers with the proper software platforms can be used to full-developed dynamic models. In the latter years' software development with such software as *MATLAB, Mathematica, POLYMATH, etc.* have developed the proper tools and capabilities to solve such models (Seborg, et al. 2011). The effort into proper modelling includes industry, for instance Outotec HSC Chemistry® 9 (Outotec, Outotec 2016). HSC Chemistry is a software developed by Outotec. It provides modelling and simulation tools for minerals processing and metals production processes. HSC Chemistry® 9 is the software used in the training platform development section, Section 3, for the process modelling and simulation of flotation; more details about it will be discussed in that section.

## 2.4. Chapter Summary

Froth flotation, either direct or indirect, is the most important separation and beneficiation process to date. It is a complex process and not fully understood, yet experimental knowledge allows quoting the parameters involved in an efficient flotation process. Several inputs and outputs exist in this process and their effects are understood, nevertheless the understanding works only as guidelines for every case and not as actual laws.

In the mineral processing industry, a new era started 30 to 40 years ago. During this time frame process control solution evolved from manual to automated control. Process control and automation have improved performance of industrial processes, yet implementing control and automation requires time and economical resources.

Process simulator is an application combining process modelling, process automated control, and dynamic simulation into a virtual platform. The virtual platform simulates the plant's behaviour with certain accuracy.

# 3. Development of Dynamic Training Simulator for a Modular Flotation Plant

The experimental part of this work consisted of the development of a dynamic simulator and control of a flotation plant. The project scope is to deliver a basic training simulator for Outotec Oy's® modular flotation plants®, upon which further tailoring can be performed to fit specific beneficiation plants in the future. Additionally, a preliminary test took place with a group of Master's level students from Aalto University. Introducing to the beneficiation simulator, a simulation of plant operation and receiving feedback to improve the graphic interface.

The training simulator is based on the modular flotation plant concept and it is simulated using the latest version HSC Sim9®. Previous simulation projects have been developed with previous versions of the simulator, HSC Sim7®. The ninth version of HSC comes with easy understanding interphase, variable definition, stream definition and equipment model. The change from HSC 7® to HSC Sim 9® involved a reduction on the capabilities of the simulator due to HSC Sim9® being still in development phase, for instance the capability of simulating reagent effect. Nevertheless, the dynamic simulation for this project will be in HSC Sim 9®. Figure 17 displays a section of the flowsheet.

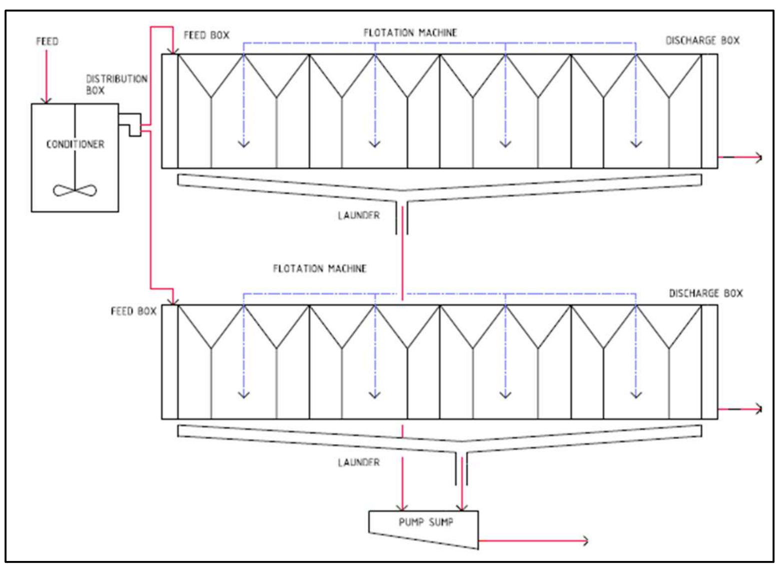


*Figure 17 Section of the flotation circuit.*

The displayed section shows the input feed to the conditioner, a mass distributor, two parallel flotation lines, launders and one pump sump. This flowsheet section displays enough material to explain the experimental section of this work and for the reader to understand the work progress.

Developing this virtual operator training has a base on four major software, HSC Sim 9®¸ SIMATIC Manager® (SIEMENS PCS 7®), Outotec Virtual Experience Manager® (VeX Manager®) and Outotec Virtual Experience Client (VeX Client®). Each of these platforms perform a vital task of the virtual operator training.

HSC Sim 9® simulates the flotation process, based on the mineralogy of the ore, the equipment dimensions and defines the chosen sets of operation variables. The latter is defined in HSC Sim9® internal tool, VeX_IO. VeX_IO is a spreadsheet in which different variables can be defined to be later read by the VeX Manager®. Siemens PCS 7® configures the automation, control and graphic interface.

The training environment set-up is done in VeX Manager®. It reads the simulation configuration from HSC Sim 9®, the automation configuration from PCS Siemens 7®, matches variables, defines initial setup and creates exercises. Finally VeX Client® display the exercise.

A deeper description of the set-up process of the different platforms and the development of the operator-training simulator is found section 3.1. Section 3.2 describes the case study with Master's degree students from Aalto University and the results from it while section 3.3 is the chapter summary.

## 3.1. Software Setup

Simulation of the flotation process was done in HSC Sim 9, software version 9.0.2. Automation setup, control programming and graphic interphase, was done in SIEMENS PCS7, software version V5.5 + SP2 + HF1. Training configuration was done in VeX Training Manager 3.0.10.0. The final training simulator was run in VeX Training Client, version 3.0.10.0.

### 3.1.1. HSC Sim® 9 Simulation Setup

The set-up of the simulation for flotation circuit and configuration of variables to connect with VeX Manager was done as following:

*i. Flowsheet*

Generation of flowsheet in HSC Sim9® starts by importing the unit diagrams, flotation cell, pumps sups, launder, as displayed in Figure 15. All imported unit diagrams are plain images. Connection and process direction is generated by streams, green arrows in figure 18. HSC defines automatically whether the streams are input or output depending on the direction of the stream.

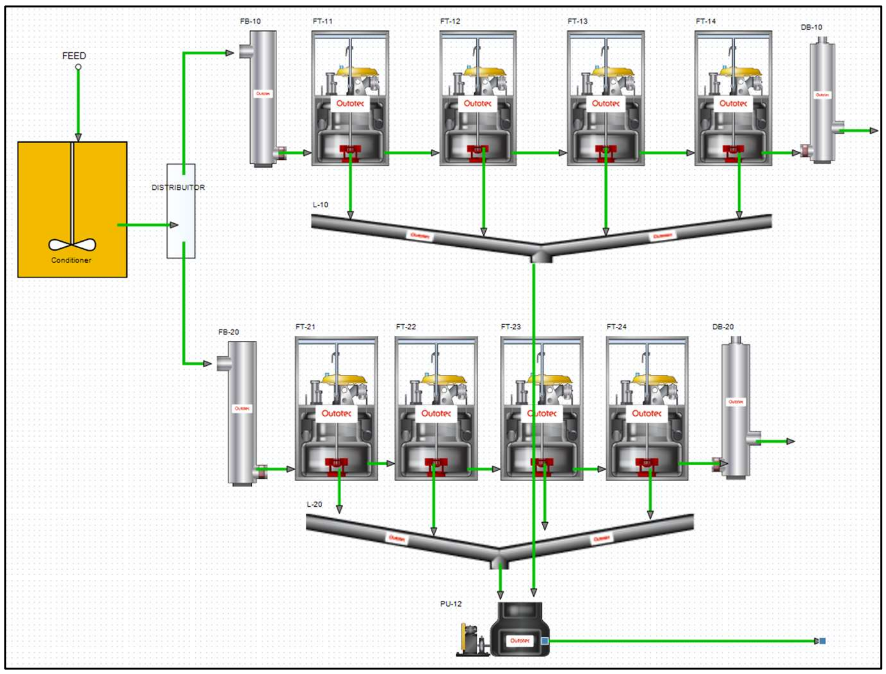


*Figure 18 Sample section of HSC Sim9® flowsheet based on Outotec flotation design.*

*ii. Define mineral setup for the feed.*

The mineral setup is defined for the main feed stream. All subsequent streams will work only with a mass flow-basis. Mineral setup involves *total flowrate, mineral species, size classes, size distribution* and *composition.* HSC Sim9® comes with a database of mineral characteristics which includes the minerals of interest in the present study. Figures 19 to 22 display the mineral setup of the feed.

| Mineral | Symbol | SG | Formula | Database ID |
|---|---|---|---|---|
| Chalcopyrite | Ccp | 4,35 | $CuFeS_2$ | |
| Sphalerite | Sp | 4,10 | $(Zn,Fe)S$ | |
| Pyrite | Py | 5,01 | $FeS_2$ | |
| Galena | Gn | 7,58 | $PbS$ | |
| Quartz | Qtz | 2,65 | $SiO_2$ | |

A1 Element

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | Element | Ccp | Sp | Py | Gn | Qtz |
| 2 | Cu | 34,63 | | | | |
| 3 | Fe | 30,43 | | 46,55 | | |
| 4 | S | 34,94 | 32,90 | 53,45 | 13,40 | |
| 5 | Zn | | 67,10 | | | |
| 6 | Pb | | | | 86,60 | |
| 7 | O | | | | | 53,26 |
| 8 | Si | | | | | 46,74 |

*Figure 19 Minerals imported for simulation.*

| Sieve Size | Lower Size | Upper Size | Fraction Av... | Size Class Label |
|---|---|---|---|---|
| 297 | 297,000 | | 420,0 | + 297 µm |
| 212 | 212,000 | 297,000 | 250,9 | 212 – 297 µm |
| 149 | 149,000 | 212,000 | 177,7 | 149 – 212 µm |
| 106 | 106,000 | 149,000 | 125,7 | 106 – 149 µm |
| 74 | 74,000 | 106,000 | 88,6 | 74 – 106 µm |
| 37 | 37,000 | 74,000 | 52,3 | 37 – 74 µm |
| 20 | 20,000 | 37,000 | 27,2 | 20 – 37 µm |
| -20 | 0,000 | 20,000 | 14,1 | -20 µm |

*Figure 20 Size Classes of Minerals.*

| Sieve Size | Weight Retained (%) | Cumulative Passing (%) | Size Class Label |
|---|---|---|---|
| 297 | 0,3 | 99,7 | + 297 µm |
| 212 | 1,2 | 98,6 | 212 – 297 µm |
| 149 | 3,6 | 94,9 | 149 – 212 µm |
| 106 | 6,9 | 88,0 | 106 – 149 µm |
| 74 | 10,8 | 77,2 | 74 – 106 µm |
| 37 | 24,9 | 52,3 | 37 – 74 µm |
| 20 | 19,3 | 33,0 | 20 – 37 µm |
| -20 | 33,0 | | -20 µm |

*Figure 21 Size Distribution of Minerals.*

| A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Σ = 100 | Mineral | Bulk | Unit | -20 µm | 20 – 37 µm | 37 – 74 µm | 74 – 106 µm | 106 – 149 µm | 149 – 212 µm | 212 – 297 µm | + 297 µm |
| ☐ | Ccp | 4,613628 | % | 6,4668 | 4,6191429 | 4,0032571 | 3,69531429 | 1,693685714 | 1,539714286 | 1,385742857 | 1,231771 |
| ☐ | Sp | 2,805189 | % | 2,9256 | 2,8646284 | 2,8036788 | 2,7427293 | 2,437981598 | 2,437981598 | 2,437981598 | 2,437982 |
| ☐ | Py | 34,36694 | % | 29,933 | 35,125675 | 36,041997 | 37,4164802 | 38,48552251 | 39,86000546 | 39,93636562 | 41,38721 |
| ☐ | Gn | 0,225177 | % | 4,7E-01 | 0,1877958 | 0,0938979 | 0,04694896 | 0,046948956 | 0,046948956 | 0,046948956 | 0,046949 |
| ☑ | Qtz | 57,98907 | % | 60,205 | 57,202758 | 57,057169 | 56,0985272 | 57,33586122 | 56,1153497 | 56,19296097 | 54,89609 |

Mineral Composition

| A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Analyzed | Element | Bulk | Unit | -20 µm | 20 – 37 µm | 37 – 74 µm | 74 – 106 µm | 106 – 149 µm | 149 – 212 µm | 212 – 297 µm | + 297 µm |
| ☐ | Cu | 1,597498 | % | 2,2392 | 1,5994075 | 1,3861531 | 1,27952596 | 0,5864494 | 0,533135818 | 0,479822236 | 0,426509 |
| ☐ | Fe | 17,40048 | % | 15,901 | 17,755323 | 17,994428 | 18,5404954 | 18,42901221 | 19,0219322 | 19,0106225 | 19,63909 |
| ☐ | S | 20,93576 | % | 19,286 | 21,357806 | 21,599753 | 22,2005069 | 21,97220911 | 22,65311422 | 22,64012623 | 23,36185 |
| ☐ | Zn | 1,882196 | % | 1,963 | 1,9220782 | 1,8811829 | 1,84028762 | 1,63581122 | 1,63581122 | 1,63581122 | 1,635811 |
| ☐ | Pb | 0,194999 | % | 4,1E-01 | 0,1626278 | 0,0813139 | 0,04065694 | 0,040656943 | 0,040656943 | 0,040656943 | 4,07E-02 |
| ☐ | O | 30,88295 | % | 32,063 | 30,464191 | 30,386656 | 29,8761166 | 30,53507752 | 29,8850757 | 29,92640875 | 29,23574 |
| ☐ | Si | 27,10611 | % | 28,142 | 26,738566 | 26,670513 | 26,2224106 | 26,8007837 | 26,230274 | 26,26655221 | 25,66035 |

Elemental Composition

*Figure 22 Mineral Composition and Elemental Composition.*

iii. *Select unit models for each imported equipment.*

All unit models are preloaded in HSC Sim9®; each model has its own mathematical equations to simulate their behaviour. For the current flotation circuit different mathematical models are linked to the unit images: flotation cells, pump sumps, perfect mixers, conditioner and mass distributor, figure 23 displays the different mathematical models associated to the unit images.

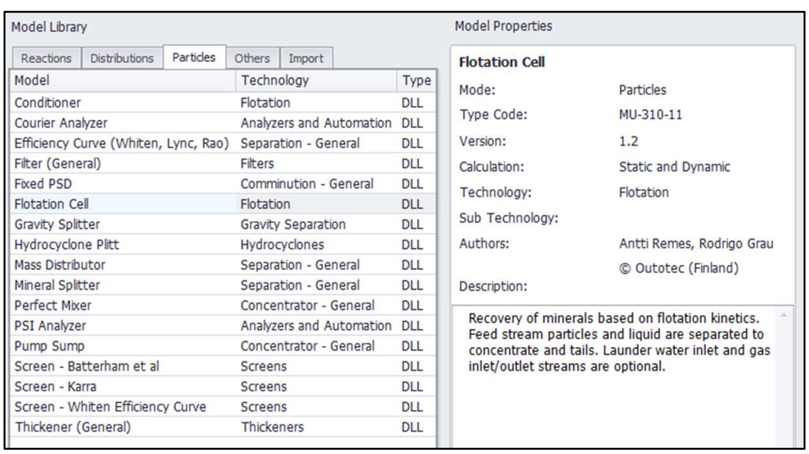


*Figure 23 Models available for minerals processing units in HSC Sim9®, Displayed Flotation Model.*

a. *Perfect Mixer:* Mixes all input material from one or several streams and passes it equally to one or several outputs (Remes, Sim Minerals Processing Unit Models 2016). Units as launders, feed-box, and discharge-box are configured with this model. The mathematical model of a perfect mixer is show in figure 24:

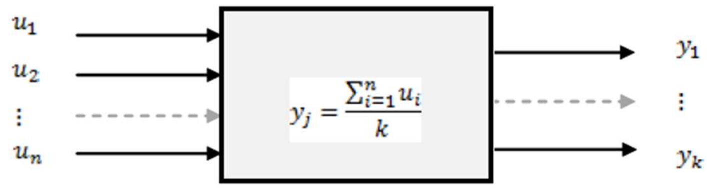


*Figure 24 HSC Sim9 perfect mixer mathematical mode (Remes, Sim Minerals Processing Unit Models 2016)l.*

Where $u_i$ is the input stream to the unit model, $y_i$ is the output stream from the unit model and k is the total output streams.

b. *Pump Sump:* The operation of this model is the same in the mathematical parameters as a perfect mixer, but the coding of this includes the capacity to store slurry, activate or deactivate pumps, overflow and capability of changing the mechanical dimensions (Remes, Sim Minerals Processing Unit Models 2016).

c. *Conditioner:* Conditioning particles by setting the flotation kinetic parameters based on three-component flotation model. The model is used for flotation calculation in the *flotation cell* model (Remes, Sim Minerals Processing Unit Models 2016). Flotation kinetic parameters is displayed in Annex I, Fig 22 to 24.

The chosen three-component model defines three possible options for flotation rate as *Fast Mass Proportions, Slow Mass Proportions* and *non-floating mass proportions*. The three-component model as dynamic simulation is calculated based on equation 11 (Remes, Sim Minerals Processing Unit Models 2016).

$$R = m_f\left(\frac{k_f t}{1+k_f t}\right) + m_s\left(\frac{k_s t}{1+k_s t}\right) + m_n \cdot 0 \qquad (12)$$

Where $R$ is the total recovery of the mineral, $m_f$, $m_s$ and $m_n$ are the mass fractions of the fast, slow and non-floatable floatability types. $K_f$ and $K_s$ are the rate constants with units of *1/min* (Remes, Sim Minerals Processing Unit Models 2016). Figure 25 and 26, display the flotation kinetics values for the mineralogy in a three element model. The shown values are default values given by HSC Sim9® and they can be modified anytime to suit a specific process. Figures 27, 28 and 29, display the mass fraction for each element and particle size. Being Ccp: Chalcopyrite, Sp: Sphalerite, Py: Pyrite, Gn: Galena and Qtz: Quartz.

| **Fast Flotation Rate Constant (1/min)** | | | | | |
|---|---|---|---|---|---|
| | Ccp | Sp | Py | Gn | Qtz |
| **+ 297 µm** | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| **212 – 297 µm** | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| **149 – 212 µm** | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| **106 – 149 µm** | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| **74 – 106 µm** | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| **37 – 74 µm** | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| **20 – 37 µm** | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| **-20 µm** | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |

*Figure 25 Kinetic Rate Constants for Fast Flotation Particles, Kf.*

| **Slow Flotation Rate Constant (1/min)** | | | | | |
|---|---|---|---|---|---|
| | Ccp | Sp | Py | Gn | Qtz |
| **+ 297 µm** | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |
| **212 – 297 µm** | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |
| **149 – 212 µm** | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |
| **106 – 149 µm** | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |
| **74 – 106 µm** | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |
| **37 – 74 µm** | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |
| **20 – 37 µm** | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |
| **-20 µm** | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |

*Figure 26 Kinetic Rate Constant for Slow Flotation Particles, Ks.*

| **Mass Proportion of Fast Particles** | | | | | |
|---|---|---|---|---|---|
| | Ccp | Sp | Py | Gn | Qtz |
| **+ 297 µm** | 0.6 | 0.05 | 0.1 | 0.2 | 0.01 |
| **212 – 297 µm** | 0.6 | 0.05 | 0.1 | 0.2 | 0.01 |
| **149 – 212 µm** | 0.6 | 0.05 | 0.1 | 0.2 | 0.01 |
| **106 – 149 µm** | 0.6 | 0.05 | 0.1 | 0.2 | 0.01 |
| **74 – 106 µm** | 0.6 | 0.05 | 0.1 | 0.2 | 0.01 |
| **37 – 74 µm** | 0.6 | 0.05 | 0.1 | 0.2 | 0.01 |
| **20 – 37 µm** | 0.6 | 0.05 | 0.1 | 0.2 | 0.01 |
| **-20 µm** | 0.6 | 0.05 | 0.1 | 0.2 | 0.01 |

*Figure 27 Mass proportion of fast-floating particles*

| Mass Proportion of Slow Particles | | | | | |
|---|---|---|---|---|---|
| | Ccp | Sp | Py | Gn | Qtz |
| + 297 µm | 0.38 | 0.3 | 0.32 | 0.4 | 0.06 |
| 212 – 297 µm | 0.38 | 0.3 | 0.32 | 0.4 | 0.06 |
| 149 – 212 µm | 0.38 | 0.3 | 0.32 | 0.4 | 0.06 |
| 106 – 149 µm | 0.38 | 0.3 | 0.32 | 0.4 | 0.06 |
| 74 – 106 µm | 0.38 | 0.3 | 0.32 | 0.4 | 0.06 |
| 37 – 74 µm | 0.38 | 0.3 | 0.32 | 0.4 | 0.06 |
| 20 – 37 µm | 0.38 | 0.3 | 0.32 | 0.4 | 0.06 |
| -20 µm | 0.38 | 0.3 | 0.32 | 0.4 | 0.06 |

*Figure 28 Mass proportion of slow-floating particles*

| Mass Proportion of Non-Floating Particles | | | | | |
|---|---|---|---|---|---|
| | Ccp | Sp | Py | Gn | Qtz |
| + 297 µm | 0,02 | 0,65 | 0,58 | 0,4 | 0,93 |
| 212 – 297 µm | 0,02 | 0,65 | 0,58 | 0,4 | 0,93 |
| 149 – 212 µm | 0,02 | 0,65 | 0,58 | 0,4 | 0,93 |
| 106 – 149 µm | 0,02 | 0,65 | 0,58 | 0,4 | 0,93 |
| 74 – 106 µm | 0,02 | 0,65 | 0,58 | 0,4 | 0,93 |
| 37 – 74 µm | 0,02 | 0,65 | 0,58 | 0,4 | 0,93 |
| 20 – 37 µm | 0,02 | 0,65 | 0,58 | 0,4 | 0,93 |
| -20 µm | 0,02 | 0,65 | 0,58 | 0,4 | 0,93 |

*Figure 29 Mass proportion of non-floating particles.*

d. *Flotation Cell:* Recovery of minerals based on flotation kinetics. Solid particles and liquid carrier in the feed are separated into concentrate and tailing stream.

e. *Mass distributor:* Distributes solids and water to several output with given ratios (Remes, Sim Minerals Processing Unit Models 2016). For the simulation used for the project development phase, shown in figure 20, the mass flow after the conditioning tank was divided into two streams with equal flowrate.

iv. *Definition of Model Parameters.*

Each model has to be configured according to their physical design. Flotation cell dimensioning is critical for this flowsheet, while the size of the pump sumps, conditioners, feed and discharge boxes cannot be specified in this version of HSC Sim. Variation in cell dimensioning will affect the overall behaviour of the flotation performance. Variation in pump sumps, conditioners, feed and discharge boxes will only affect, in this specific simulation, the time of obtaining a final concentrate. Table 2 shows parameters that can be changed in HSC for flotation cells and the other equipment in flowsheet.

*Table 2 Equipment models parameters in HSC Sim9®. Real values are property of Outotec Oy® and are not published in this document.*

| | | | | |
|---|---|---|---|---|
| Flotation cell | | | | |
| Net Volume | Pulp Area | Froth Area | Lip Height | Lip Length |
| Rotor Diameter | Valve Type | No. of Valves | Valve Size | Step to Next Cell |
| Level Sensor | Level Measurement Method | Froth Volume Calculation | Froth Volume Percentage | Froth Thickness |
| Gas Hold-up | Bubble size | Air Flowrate | Air Recovery | Rotor Speed |
| Froth Recovery | Entrainment | Carry Rate | Max Forth Carry Rate | Max Froth Carry Rate |
| Max Lip Load in Use | Max Lip Load | Max Froth Thickness | Concentrate Solids | Tail Solids |
| Feed & Discharge Boxes, Mass Distributor, Launder | | | | |
| - | - | - | - | - |
| Conditioner | | | | |
| Flotation kinetics | Volume | Height | - | - |
| Pump Sump | | | | |
| Volume | Height | Default Level | Pumps in use | Max Flowrate |

*v. VeX_IO Variable Definition.*

The variable definition for VeX Manager is defined in the VeX_IO is spreadsheet tool. VeX_IO allows the definition of two types of variables, set-variables (SetVar) and get variables (GetVar). SetVar are variables whose value is modified externally, in this case by Siemens PCS7®, and introduced to HSC for simulation purposes, while GetVar are variables simulated by HSC and their value is exported as read-only.

The variables, either SetVar or GetVar, can be imported to the VeX_IO spreadsheet from any of the values that can be obtained from the model. Values can be read from any of the “input/output” streams and/or the “runtime values” which are the dynamic simulation parameters of the models, adding capabilities to the training platform. Table 3 shows the definition of SetVar and GetVar in HSC Sim9® for the required equipment.

*Table 3 GetVar and SetVar definition in HSC Sim9®*

| SetVar | GetVar |
|---|---|
| 1. Flotation Cell:<br>i. Air Valve Opening [%].<br>ii. Start/Stop Motor [I/O].<br>iii. Level Valve Opening [%].<br>2. Pump Sump:<br>i. Pump speed set point [%].<br>ii. Open/close valve [I/O].<br>iii. Start/Stop pump [I/O]. | 1. Flotation Cell:<br>i. Air flow-rate [$m^3$/min].<br>ii. Feedback Start/Stop motor [I/O].<br>iii. Cell Level [mm].<br>2. Analyser:<br>i. Copper weight [wt-%].<br>ii. Iron weight [wt-%].<br>3. Slurry:<br>i. Slurry throughput [tph].<br>ii. Total solids [tph].<br>4. Pump Sump:<br>i. Level measurement [%].<br>ii. Feedback Start/Stop pump [I/O].<br>iii. Pump speed feedback [%]. |

For example, based on table 3, the air valve opening, pump motor and flotation cell motor are simulated by SIEMENS PCS 7® while the air flow-rate input to the cell and the feedback value of the motor as start or stop is simulated by HSC Sim9®. The rest of the SetVar and GetVar follow a similar behaviour.

### 3.1.2. SIEMENS PCS 7 Setup

i. Graphic Interphase.

Graphic interface through which the end-user interacts with the automation system is created in WinCC application, part of SIEMENS PCS7 pack. Figure 30 display the graphic interphase of the same flowsheet section and without control elements.

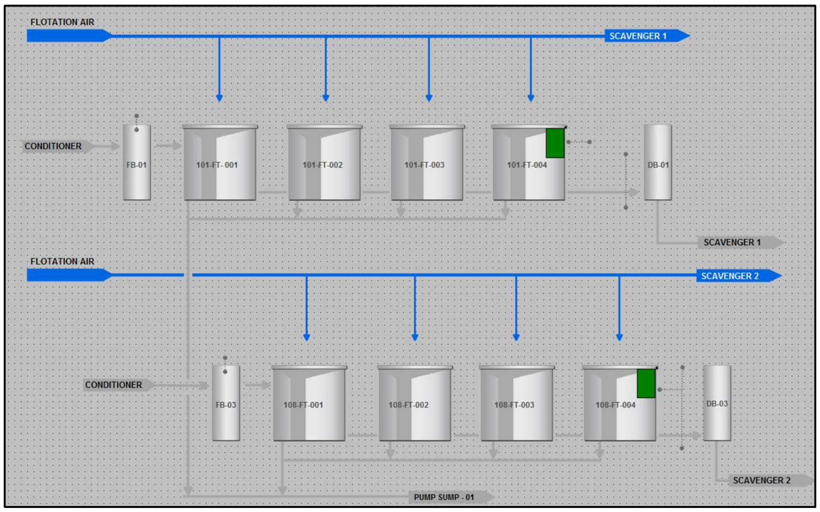


*Figure 30 Graphic interphase for two parallel flotation circuits, Based on Figure 21.*

ii. Process control logic.

During this phase the control logic was programmed and the representation of the different instrumentation was sent to the graphic interface. The process control of the simulation is programmed by Function Block Diagrams programming language. Function block diagram is a graphical language for PLC programming (Bolton 1996). The blocks are programmed by linking with streams between inputs and outputs from the different blocks, as shown in Figure 32 (SIEMENS 2003).

The connection between blocks is done as displayed in figure 31. The inputs in the block goes into the left side of the block, while the outputs from the right side of it.

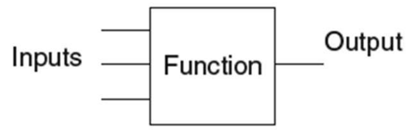


*Figure 31 Function block (Bolton 1996).*

Displayed in figure 32, 5 blocks interconnected generating the control of a motor, highlighted in red. The rest of the blocks in image 32 are the can be a logic controller, an interlock, an error message, feedback of a process variable, etc. The rest of the plant instrumentation, valves, value displays, pump sumps, flow-meters, etc. are set in by creating different blocks diagrams and creating the links between them.

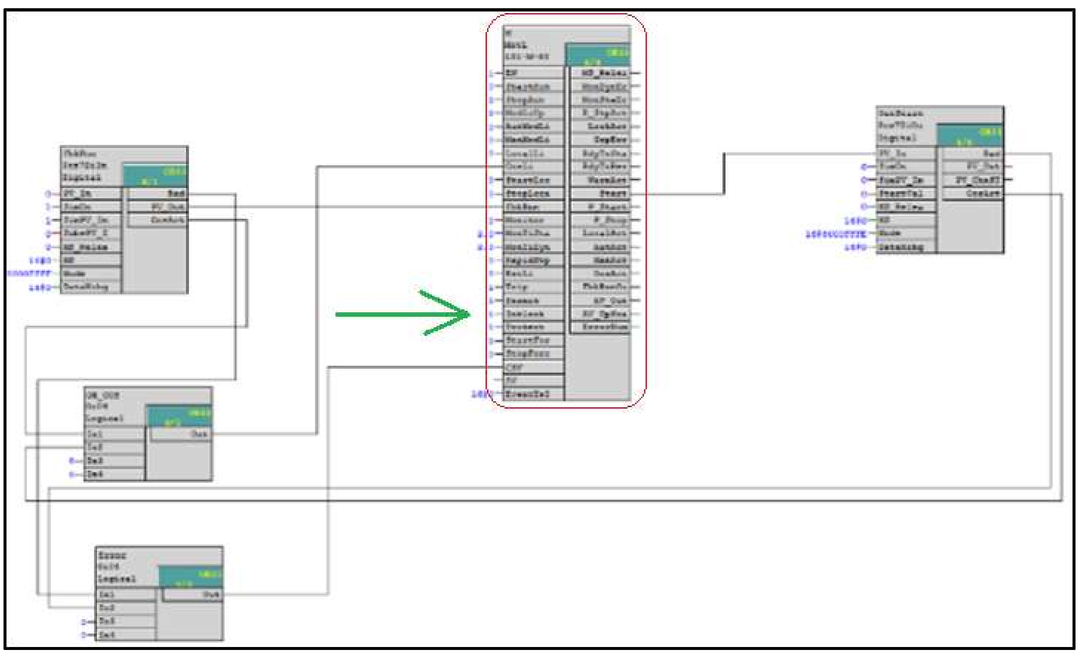

*Figure 32 Function Block Diagram of a Motor.*

After all the instruments are programmed, the process is compiled and downloaded to the PLCSim. PLCSim is a PLC simulator part of the SIEMENS PCS7® pack. Compiling the generated programming is putting together the changes made, and downloading to the PLCSim is sending the generated information about the control, the instrumentation and any change done into the PLCSim computer. The function of the PLCSim is to simulate the PLC controlling the different instruments, without it the instruments will not operate in the simulator.

Every of the generated block diagrams have a graphic representation of their instrument which is displayed in the graphic interface and included at the moment of downloading the blocks into the PLC, as shown in figure 33. In the same image it is observable the graphic representation of the motor of the block diagram displayed in figure 32.

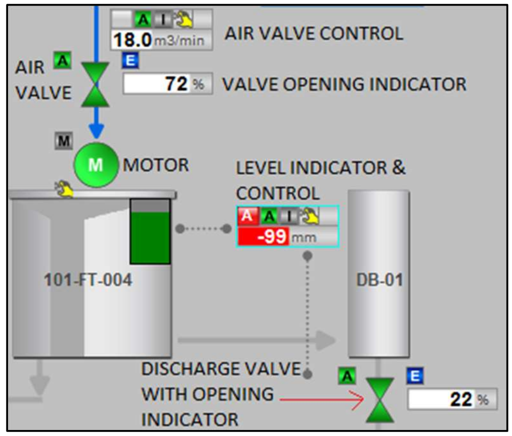


*Figure 33 Flotation cell with discharge box and control elements.*

From figure 31, it is observable that all the blocks are made of small elements (marked in green), these elements are called tags. Depending on the block is the amount of tags it is made of, and each tag has a specific action, for example: the “SimOn” tag can either start or stop the simulation of a block during operation.

The tags are how variables are identified in each block, the tag name is automatically changed when the block name is changed. Tags are used during a process called “Tag Mapping” which consists of the matching of simulation variables between HSC Sim9® and SIEMENS PCS7® by VeX Manager. The tag mapping process is furtherly explained in the next section.

### 3.1.3. Virtual Experience Manager Setup: training simulator

Virtual Experience Manager, VeX Manager, and Virtual Experience Client, VeX Client are the last two platforms to obtain the training simulator of the flotation circuit. The training platform simulator was developed with VeX Manager based on HSC Sim9® and SIEMENS PCS7®. The simulator is activated and the training takes place in VeX Client.

VeX Manager software imports the HSC Sim9® simulation along with the defined variables in the VeX_IO spreadsheet and the automation tags from PCS, Figure 34 displays both software imported to VeX Manager. After import variables from HSC and PCS must be matched, this process is known as tag mapping.

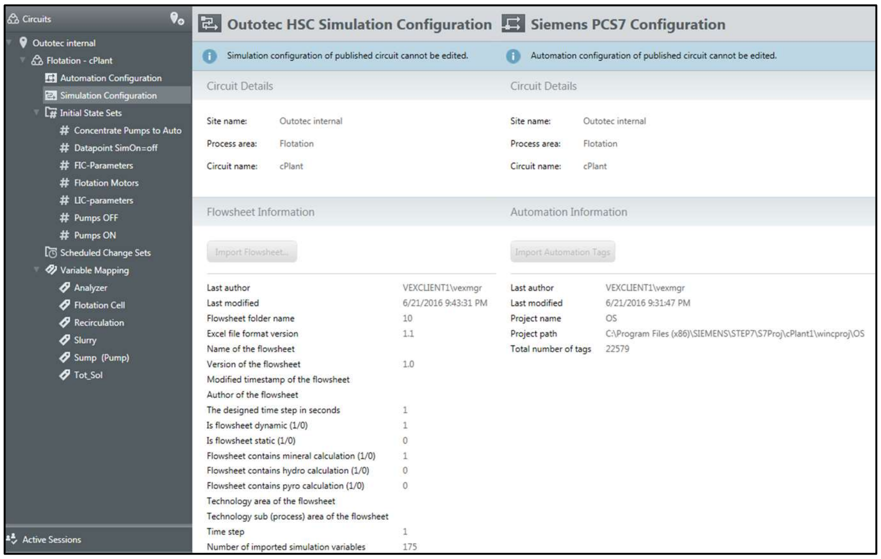


*Figure 34 Import of HSC Simulation and PCS Configuration*

Tag mapping reads a variable from VeX_IO (HSC) and assigns it an automation tag (PCS) and depending on the nature of the simulation, either simulated in HSC or PCS, also assigns a Simulation Mode Tag. For example, considering the level control of the flotation cell described by figure 33 and table 3. From table 3, we defined SetVar: level valve opening and GetVar: cell level. The respective elements for SIEMENS PCS7®, programmed as function blocks, are displayed in figure 33 as "level control & indicator" and "discharge valve with opening indicator".

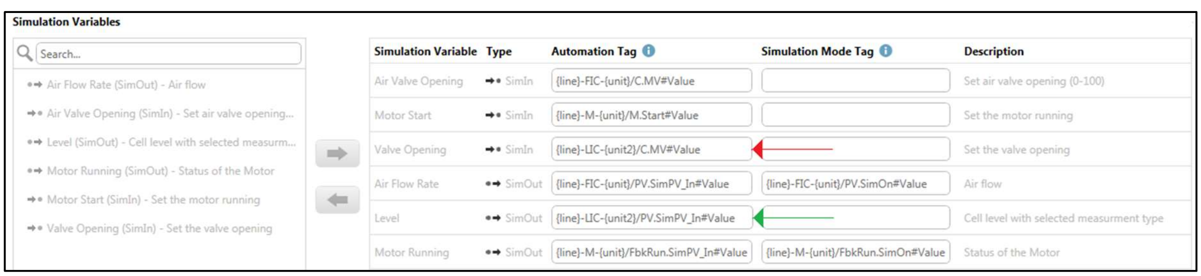


*Figure 35 Tag Mapping of a flotation cell.*

The tag mapping process for the mentioned level control is next described:

i. The simulation variable “Level” was the previously described as “Level Indicator and Control” is tagged to the automation tag *“PV.SimPV_In#Value”* of the CFC of a “Level Indicator Control (LIC)”, highlighted in green in figure 35.

ii. The simulation variable “Valve Opening” is the previously described as “Discharge valve with opening indicator” is tagged to the automation tag “*C.MV#Value”* of the CFC of a “Level Indicator Control (LIC)”, highlighted in red in figure 35.

Similar process is done for all the block diagrams. After the tag mapping process of the mentioned example. The level simulation is calculated in HSC Sim9®; the value is read by SIEMENS PCS7® and displayed in “Level Indicator and Control”. SIEMENS PCS7® controls the “Discharge Valve with Opening Indicator” hence controls the level of the flotation cell. The valve opens or closes depending on the measured value of the level and the set-point. A similar process was repeated for the full extension of the flowsheet, covering different instruments like air-flow valves, pump sumps, level indicators, mass flow, sampling points, valves, level control and pump sumps.

The training exercise development is also done in VeX Manager. This process consists on creating a time scheduled change within the variables tag-mapped. For example, changing the tag “SimOn” of a pump sump simulated in PCS7® from being “on” into being “off”, from a value of “1” to a value of “0”; or also can change the federate into dropping or increasing drastically.

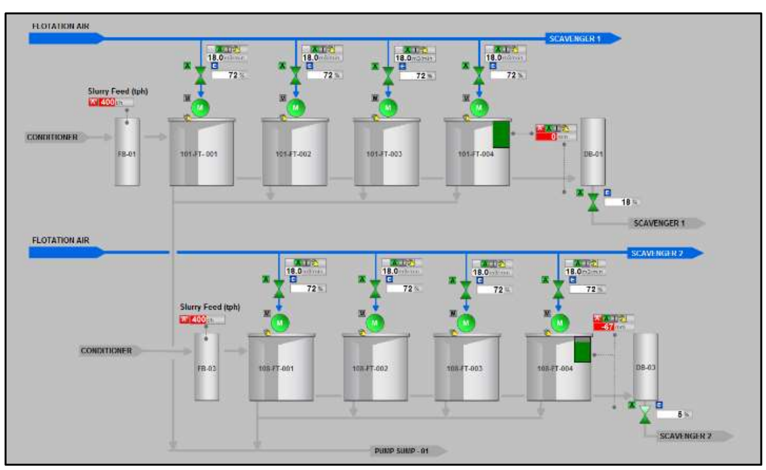


*Figure 36 Graphic interphase based on Figure 21, with CFC and Blocks operating.*

Vex Client is the final software in charge of launching the simulator. This software is capable of displaying, connecting and activate the user interaction with the virtual environment. Figure 36 shows the section of flowsheet during the simulation, controls, valves and sampling points operating.

## 3.2. Case Study

The first version of the training platform was delivered to Aalto University Master's students. It was held after a 4-month period after the beginning of the development process during a 3-hour session in Outotec headquarter in Matinkylä, Finland. The goal of the session was mainly to introduce the students to a mineral processing simulator software, to a flotation simulator and to obtain feedback regarding the overall programming of the simulator, graphic interface, instruments and to get improvement areas which were not foreseen by the developer.

The Aalto students received a basic training on the simulator with the purpose of teaching them how to interact with the virtual environment. During the training session the participants received a feedback form, this form was developed to obtain an opinion from the participants without inducing personal opinion from the developer. The feedback form filled by the Aalto University Master's students can be seen in Annex 1, figures 37 to 42. The feedback obtained from the students can be summarized as:

1. The connection between the process simulator and the control logic simulator was not perfectly established. No change in final recovery after changing stream and valve values.
2. Not all the displayed icons were accessible.
3. Un-easy interaction and operation.
4. Control/Function block icons were not placed clearly showing the intended streams.
5. Pop-up windows are repeatedly displayed.

Further improvement in the training simulator was based on feedback comments and from Outotec staff (Liski 2016). The latter feedback includes:

1. Graphic interphase modification:
    a. Fit two parallel flotation circuits into the same screen.
    b. Remove unused block diagram icons: pH, eH and un-used valves.

    c. Remove unused screens: reagent dosing, extra pipelines, flotation lines.
2. Finalizing the programing, tag connections, CFC connections and Instrument configuration.
    a. Level display.
    b. Final weight recovery display.
    c. Addition of sampling points.

The list changes generated can be seen in table 4.

*Table 4 List of changes implemented after feedback.*

| | |
|---|---|
| 1. Increase to two flotation lines per screen. | 2. Remove unused valves. |
| 3. Replace instruments. | 4. Reduce the amount of level display. |
| 5. Remove unused streams. | 6. Remove Eh and pH displays. |
| 7. Flotation cell graphic reduction. | 8. Remove tendencies chart. |
| 9. Interactive level display programming. | 10. Include pump sumps into flotation line screens. |
| 11. Pump sump final programming. | 12. Weight recovery display programming. |
| 13. Main screen display modification. | 14. Reagent dosing screen and streams. |
| 15. Addition of sampling points. | |

From the Aalto Overall and the Outotec feedback, the simulator graphic interface was changed either in every screen and in the total amount of screens, reducing it from 14 to 9. This reduction decreased the navigation stress generated by the excessive amount of different screens and the similarity between them. The screens layout was having an improved instrument arrangement and a better clarity on the different elements and what are they displaying and/or controlling. Feedback comments such as: “Pop-up windows are repeatedly displayed” were not changed, since this situation is part of the core code of the VeX Manager / VeX Client and out of the scope of the project.

### 3.3. Chapter Summary

The training simulator was based on Outotec conceptual design of a modular flotation plant. The training simulator was created in four different software platforms HSC Sim9®, SIEMENS PCS7®, Virtual Experience Manager and Virtual Experience Client. Each software platform is specialized on a specific task.

HSC Sim9® performs the metallurgical simulation of the flotation circuit and the definition of simulation variables in VeX_IO. VeX_IO is the spreadsheet tool of HSC that permits the communication between HSC variables and VeX Manager. HSC Sim9® variables can be defined as SetVar or GetVar depending on the need, GetVar are variables simulated and controlled by HSC and read only by SIEMENS PCS7®, while SetVar are variables simulated and controlled by SIEMENS PCS7®.

SIEMENS PCS7® performs the graphic interphase the control and the automation simulation. All the control instruments, the control parameters, the instruments programming and the tag definition for every instrument are developed in this software.

Virtual Experience Manager software compiles the flotation circuit simulation and the graphic interphase, control and automation simulation into one and it is possible to create scheduled changes in the flowsheet to improve the real life experience. The tag mapping process is carried out in VeX Manager, it is the key task to control and automate properly the HSC Sim9® flowsheet with PCS7®.

A clear variable naming in HSC Sim9® and SIEMENS PCS7® is a critical point for the development of the training platform. Inaccurate naming can lead to confusion and to a performed developed tag mapping, hence the control and automation will not operate properly.

# 4. Results and Conclusions

The training platform tool was developed in a 5-month period, after which the training tool was delivered to Outotec Oy®. The final version of the training tool went under revision of different groups and persons which gave feedback for the improvement of the same. The delivered version of the training platform tool is capable of simulating the modular flotation plant concept, to perform the flotation process separation with the introduced ore feed, flotation kinetics, mechanical equipment characterization, to give an approach to the real operation of it to the user and to simulate different variations commonly found in site, such as pump break down and/or non-stable ore feed tonnage into the process.

The delivered training platform is only a baseline for future versions. Future developments can be built from this platform and can be expanded towards having additional control parameters, instrumentation, ores with different metallurgy or different characteristics of the flotation bank, more or less flotation cell tanks, depending on the specific application, among all the minerals processing upgrading, comminution or dewatering processes which can be simulated by HSC Sim9®.

The limitations on the version 9.0.2 of HSC Sim9® and the time allowed for the development of the training tool represented a major limiting factor for the development of the final project. The utilized version did not permit the change of ore feed after the unit model selection, which during the whole project development restricted the different flowsheets created and the flexibility to develop ore-type variations. HSC Sim® in the mentioned version is not capable of simulating the effect of addition of flotation reagents into the flotation process which reduced the complexity of the flowsheet developed. Regardless of these limitations the initial objective of the project was achieved and the training simulator tool was developed. Nevertheless HSC Sim9® is under continuous development and in the future versions it might be possible to simulate the mentioned processes.

This kind of developments and projects impact in different levels, the industry with the continuous improvement they have set as a perpetual goal, higher degree students allowing them to participate in this kind of developments and to use the tools that are aimed for industrial application and the academia allowing the continuous positive cooperation between industry and universities.

## Annex I

Outotec

**VIRTUAL EXPERIENCE TRAINING – FLOTATION EVALUATION**

1 (2)

**VEX CPLANT, BASIC COURSE**

VeX Environment ⇒ Understandable but not simple for First time users.

| | | ☹ | | 😐 | | ☺ | |
|---|---|---|---|---|---|---|---|
| User Friendly (Can anyone can come and use it?) | Poor | ☒ | ☐ | ☐ | ☐ | ☐ | Excellent |
| Clarity of flowsheet (what leads to where?) | Poor | ☐ | ☐ | ☐ | ☐ | ☒ | Excellent |
| Navigation (how easy you went to where you wanted?) | Poor | ☐ | ☐ | ☒ | ☐ | ☐ | Excellent |
| Charge of screens? (Too many objects?) | A lot!!! | ☐ | ☐ | ☐ | ☒ | ☐ | Just Enough |
| How would you evaluate the overall arrangements and the training environment? | Poor | ☐ | ☐ | ☐ | ☒ | ☐ | Excellent |

How would you improve it?

| Screen | Improvement |
|---|---|
| Automation Tools | ⇒ I couldn't be able to figure out how to connect it. ⇒ Could be simple to connect it. ⇒ Group command could be clear. ⇒ Don't understand what it means. |
| Scavenger Flotation Line I | ⇒ I was trying to open process water flow but I couldn't! ⇒ It would be nice if there is a means to access the process |
| Rougher Flotation Line I | ⇒ was hard to open the valves but finally I am able to open them. ⇒ |
| In general | ⇒ It would have been nice to see the result of the changes (what ever change) I make on the result. ⇒ |

*Figure 37 Feedback from Master's degree student 1 of 6.*

Outotec

**VIRTUAL EXPERIENCE TRAINING – FLOTATION EVALUATION**

1 (2)

**VEX CPLANT, BASIC COURSE**

VeX Environment

| | | ☹ | | 😐 | | ☺ | |
|---|---|---|---|---|---|---|---|
| User Friendly (Can anyone can come and use it?) | Poor | ☐ | ☐ | ☐ | ☒ | ☐ | Excellent |
| Clarity of flowsheet (what leads to where?) | Poor | ☐ | ☐ | ☒ | ☐ | ☐ | Excellent |
| Navigation (how easy you went to where you wanted?) | Poor | ☐ | ☐ | ☐ | ☐ | ☒ | Excellent |
| Charge of screens? (Too many objects?) | A lot!!! | ☐ | ☐ | ☐ | ☐ | ☒ | Just Enough |
| How would you evaluate the overall arrangements and the training environment? | Poor | ☐ | ☐ | ☐ | ☒ | ☐ | Excellent |

How would you improve it?

| Screen | Improvement |
|---|---|
| Rougher Flotation Line 1 & 2 | There now is only pH ~~one~~ sensor on the roughers. Its not really clear if it's the pH for all the tanks or for one stream. ~~Also~~ Perhaps put it next to the flowsheet and add pH to scavengers and cleaners also |
| | |
| | |
| | |

*Figure 38 Feedback from Master's degree student 2 of 6.*

Outotec

**VIRTUAL EXPERIENCE TRAINING – FLOTATION EVALUATION**

1 (2)

**VEX CPLANT, BASIC COURSE**

VeX Environment

| | | ☹ | | 😐 | | ☺ | |
|---|---|---|---|---|---|---|---|
| User Friendly (Can anyone can come and use it?) | Poor | ☐ | ☐ | ☒ | ☐ | ☐ | Excellent |
| Clarity of flowsheet (what leads to where?) | Poor | ☐ | ☐ | ☐ | ☒ | ☐ | Excellent |
| Navigation (how easy you went to where you wanted?) | Poor | ☐ | ☐ | ☐ | ☒ | ☐ | Excellent |
| Charge of screens? (Too many objects?) | A lot!!! | ☐ | ☐ | ☒ | ☐ | ☐ | Just Enough |
| How would you evaluate the overall arrangements and the training environment? | Poor | ☐ | ☐ | ☐ | ☒ | ☐ | Excellent |

How would you improve it?

| Screen | Improvement |
|---|---|
| Basic Screen | Detailed tooltips would be awesome. Also seeing tooltips for greyed out buttons as well as clickable ones would be nice |
| Everything<br>Found it lol. | ~~THERE TOTALLY NEEDS TO BE A BACKWARDS/FORWARDS BUTTON IN THE CLIENT!~~<br>~~Also, when you click something to move to another screen, you need to be able to go back in case you misclick~~ |
| Rougher flotation line 1 | When you click on 101-FIC-104/C multiple times, the program opens a new 101-FIC-004/C window for every click instead of just highlighting the existing window. Same thing with 602-FIC-011/V. Probably everything else too. |
| Process unit screens. | For training it would be nice to see a diagram, a bit like a minimap in a videogame, that indicates where the operator is in the flowsheet. |

*Figure 39 Feedback from Master's degree student 3 of 6.*

Outotec

**VIRTUAL EXPERIENCE TRAINING – FLOTATION EVALUATION**

1 (2)

**VEX CPLANT, BASIC COURSE**

VeX Environment

| | | ☹ | | 😐 | | ☺ | |
|---|---|---|---|---|---|---|---|
| User Friendly (Can anyone can come and use it?) | Poor | ☐ | ☐ | ☐ | ☒ | ☐ | Excellent |
| Clarity of flowsheet (what leads to where?) | Poor | ☐ | ☐ | ☒ | ☐ | ☐ | Excellent |
| Navigation (how easy you went to where you wanted?) | Poor | ☐ | ☐ | ☐ | ☐ | ☒ | Excellent |
| Charge of screens? (Too many objects?) | A lot!!! | ☐ | ☒ | ☐ | ☐ | ☐ | Just Enough |
| How would you evaluate the overall arrangements and the training environment? | Poor | ☐ | ☐ | ☐ | ☐ | ☒ | Excellent |

How would you improve it?

| Screen | Improvement |
|---|---|
| Flotation Rougher | Air feed amount could be more clearer that it belongs to air stream |
| | |
| | |
| | |

*Figure 40 Feedback from Master's degree student 4 of 6.*

Outotec

**VIRTUAL EXPERIENCE TRAINING – FLOTATION EVALUATION**

1 (2)

**VEX CPLANT, BASIC COURSE**

VeX Environment

| | | ☹ | | 😐 | | ☺ | |
|---|---|---|---|---|---|---|---|
| User Friendly (Can anyone can come and use it?) | Poor | ☐ | ☐ | ☑ | ☐ | ☐ | Excellent |
| Clarity of flowsheet (what leads to where?) | Poor | ☐ | ☐ | ☐ | ☐ | ☑ | Excellent |
| Navigation (how easy you went to where you wanted?) | Poor | ☐ | ☐ | ☑ | ☐ | ☐ | Excellent |
| Charge of screens? (Too many objects?) | A lot!!! | ☐ | ☐ | ☐ | ☐ | ☑ | Just Enough |
| How would you evaluate the overall arrangements and the training environment? | Poor | ☐ | ☐ | ☐ | ☑ | ☐ | Excellent |

How would you improve it?

| Screen | Improvement |
|---|---|
| | |
| | |
| | |
| | |

*Figure 41 Feedback from Master's degree student 5 of 6.*

Outotec

**VIRTUAL EXPERIENCE TRAINING – FLOTATION EVALUATION**

1 (2)

**VEX CPLANT, BASIC COURSE**

VeX Environment

| | | ☹ | | 😐 | | ☺ | |
|---|---|---|---|---|---|---|---|
| User Friendly (Can anyone can come and use it?) | Poor | ☐ | ☐ | ☐ | ☑ | ☐ | Excellent |
| Clarity of flowsheet (what leads to where?) | Poor | ☐ | ☐ | ☐ | ☑ | ☐ | Excellent |
| Navigation (how easy you went to where you wanted?) | Poor | ☐ | ☐ | ☐ | ☑ | ☐ | Excellent |
| Charge of screens? (Too many objects?) | A lot!!! | ☐ | ☐ | ☐ | ☑ | ☐ | Just Enough |
| How would you evaluate the overall arrangements and the training environment? | Poor | ☐ | ☐ | ☐ | ☑ | ☐ | Excellent |

How would you improve it?

| Screen | Improvement |
|---|---|
| Alarm log | → should be more clear<br>→ notification is already good<br>→ If HL alarm reached, it might be better to have a pop-up warning |
| | |
| | |
| | |

*Figure 42 Feedback from Master's degree student 6 of 6.*

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